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EXPLOSIVE RESPONSE TO LOW SPEED SPIGOT IMPACT

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Abstract

Safety is of paramount importance in the handling, processing and storage of explosives. Low speed impact has been identified as a credible ignition source that can occur during accident scenarios. To provide experimental evidence for the assessment of the threat created by such impacts, work has been ongoing at AWE and LLNL to measure the response of explosives to low speed spigot impact over a range of scales. In this paper the experimental results from impacts on three different HMX based Plastic Bonded Explosives, are presented. The explosives ranged from 90% to 95% by weight HMX content and had three different binders (HTPB Polyurethane, Viton A and a blend of NC and K10 liquid plasticizer). The experiments represent a basic spigot impact into bare unconfined explosives. Initial modelling results using the High Explosive Violent Reaction Model HERMES, as implemented in the LSTC finite element code LS-DYNA, are presented. The modelling results are compared qualitatively with the experimental data. In particular, the locations of predicted high values of the HERMES ignition parameter are compared with the available evidence of ignition location. Plots of the growth of the reaction with time are also presented.

Introduction

Low speed impact has been identified as a credible ignition source that can occur during accident scenarios. To provide evidence based assessment of the threat posed by such impacts, work has been ongoing at AWE and LLNL to measure the response of explosives to low speed spigot impact over a range of scales. Work has been reported previously on the impact response of explosive in the LLNL Steven Test [I], the AWE Steven test vehicle [II] and in a controlled Spigot Intrusion Vehicle [III], the results from these experiments give an indication of the threshold velocity for reaction under different confinement. These experiments afford heavy confinement which not only masks the response of the explosive but in many cases is not representative of a real accident scenario. In this series of experiments the aim is to impact the explosives in a transparent vehicle that allows the visualisation of the material motion and the monitoring of the onset and growth of reaction. High speed video footage along with blast overpressure measurements can then be used as metrics of the violence of the explosion.

Development of a predictive model for ignition in projectile impact scenarios has been ongoing at AWE for a number of years. The current model in use at AWE to assess explosive reaction is the code HERMES as implemented by Jack Reaugh of LLNL in the LSTC finite element code LS-DYNA.

Experimental

Material

Three different plastic bonded explosives were used in this series of experiments, ranging from 90% to 95% HMX content by weight. PBX1 has 91% HMX explosive content and a mixed binder of 1% Nitrocellulose and 8% K10 Liquid plasticiser (K10 is a mix of Trinitroethybenzene and Dinitroethylbenzene) PBX1 was isostatically pressed to 1.84gcm^{-3} and machined to size. PBX2 has 95% HMX explosive and 5% HTPB Polyurethane binder and was isostatically pressed to 1.78gcm-3 and machined to size. PBX3 has 90% HMX explosive content and 10 % Viton A binder; this sample was die-pressed to 1.83gcm^{-3}.

TABLE 1 – Material compositions

HE	Density gcm^{-3}	Composition	% by weight
PBX1	1.84	HMX Type B Nitrocellulose K10	91 1 8
PBX2	1.78	HMX type B HTPB Polyurethane	95 5
PBX3	1.83	HMX type B Viton A	90 10

All samples tested used Bridgewater HMX Type B powder, which has a bimodal particle size distribution with the predominant particle size of less than 45um.

Test Design

The test vehicle was designed to represent a thin spigot impacting a bare HE charge with a semi rigid back surface. The cylindrical target vehicle has a 10mm thick steel base with a highly polished Perspex confining ring of height 25.4 mm around the explosive sample of height 25.4 mm and radius 12.7 mm. The steel base plate has a 5mm diameter recess cut in the centre of the rear face. This feature is designed to produce a steel flyer when a reaction occurs in the sample. Photon Doppler Velocimetry is used to record the velocity of the flyer. The mild steel projectile with a 28 mm long hardened steel spigot of radius 3.175 mm axially mounted at the end was fired from a 50mm smooth bore single stage gas gun. This spigot length allows it to penetrate the full depth of the explosive charge. The polished Perspex confining ring provides minimal mechanical confinement to the charge whilst allowing the explosive material response to be observed normal to the impact axis.

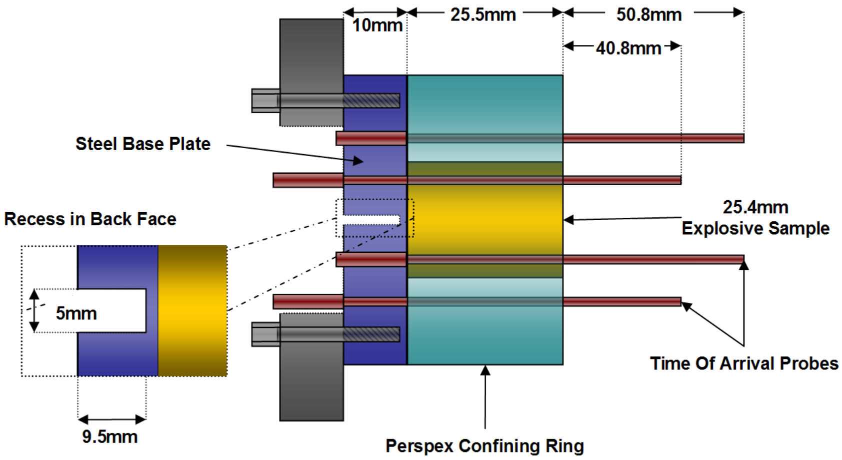


FIG 1 – Spigot test design

The muzzle velocity of the projectile was measured with two wire coils spaced 100mm apart placed at the muzzle of the gas gun. This provides a reliable muzzle velocity irrespective of the projectile shape.

Two levels of electrical short time of arrival probes positioned at 60^0 intervals around the charge, one set of three at 50.8mm and a second at 40.8mm from the front face of the explosive. As the projectile approached the vehicle the probes are impacted by the projectiles leading face, the time recorded between the two probe levels allows the axial velocity to be accurately calculated at the time of impact. Using three independent probes an approximation of the tilt of the projectile with respect to the explosive surface at impact can be found by means of a straightforward vector calculation. The probes thus allow a full description of the impact conditions to be formulated.

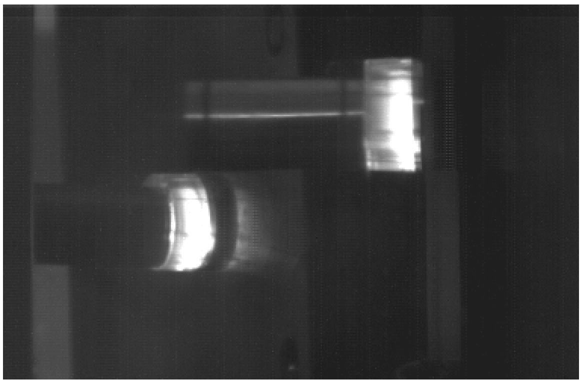
FIG 2 – vehicle installed in the firing chamber

The material movement and the onset of reaction in the HE was captured using a Photron APX high speed video camera viewing through the Perspex confinement normal to the impact axis. The onset and growth of the reaction could be monitored. Blast overpressure gauges were arranged around the test to monitor any overpressure developed by the reaction.

Results

PBX1

Eight shots were completed on the PBX1 material, initially at 44ms^{-1} and decreasing to find the threshold, however ignitions occurred down to 14.2 ms^{-1}. The threshold velocity for this material as measured in the Steven test is 63±1 ms^{-1}[IV] and for an 8mm spigot the threshold velocity was 17-27 ms^{-1}(III), the threshold for reaction for PBX1 in this configuration was expected to lie in the region of 20-30 ms^{-1}.



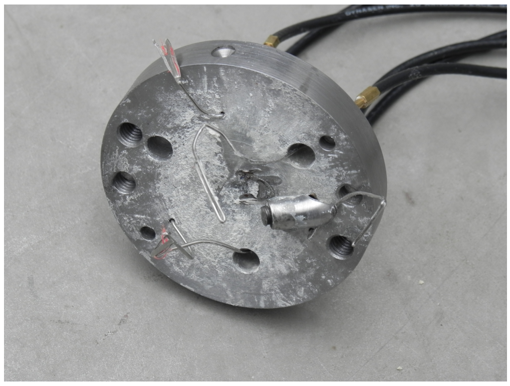


FIG 3 – Ignition at the rear surface and remnants from Shot 02, PBX1

From the high speed video footage it was seen that in every case the spigot penetrated to the full depth of the explosive, all ignitions occurred as the spigot pinched material at the back surface. A threshold velocity for PBX1 could not be measured; the tilt of the projectile at the point of impact could play an important role, introducing a sharp edge at impact with the rear surface in place of a distributed area.

TABLE 2 – Results for PBX1

Shot	Muzzle Velocity ms^{-1}	Pin Probe Velocity ms^{-1}	Reaction	Spigot Tilt Deg
02	47.17	44.4	Y	0.7
03	39.7	40.0	Y	0.6
04	35.6	-	Y	-
05	34.13	33.0	Y	0.5
06	25.24	24.9	Y	-
13	19.6	18.7	Y	0.6
14	14.13	14.2	Y	1.6

PBX2

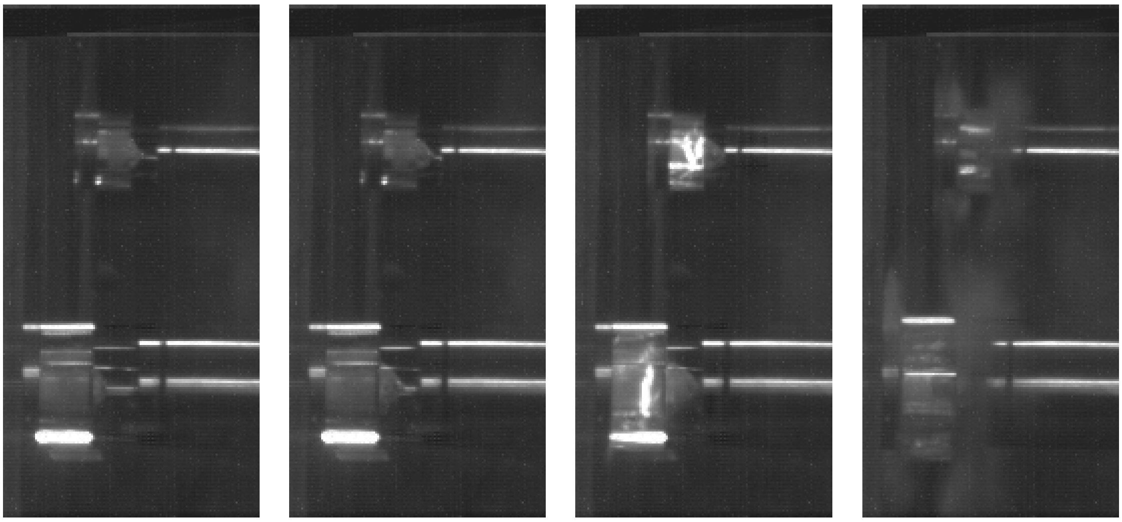
In the case of the lower density PBX2 material the threshold for reaction was 19.0 – 21.6 ms^{-1}. In this case is can be seen that ignition occur in similar conditions to the PBX1 as the spigot pinches the rear surface of the vehicle. The increased material strength in PBX2 over PBX1 due to a stiffer binder requires a higher impact speed to penetrate to the full depth of the charge, leading to the higher impact threshold velocity. As the impact velocity is increased the violence as the reactions stays very similar, producing large fragment from the Perspex ring but not consuming the full sample.

TABLE 3 – Results for PBX2

Shot	Muzzle Velocity ms^{-1}	Pin Probe Velocity ms^{-1}	Reaction	Spigot Tilt Deg
11	27.13	26.5	Y	0.6
12	22.19	21.6	Y	0.7
10	19.36	19.0	N	1.0

PBX3

As opposed to PBX 1 and PBX2, PBX3 was seen to ignite during the penetration by the spigot, with ignitions occurring at 7.4mm penetration at 20.0 ms^{-1} and 9mm penetration at 16.2 ms^{-1}.



0.5ms 0.65ms 0.8ms 0.95ms

FIG 4 – Ignition at 7.4mm penetration, time from impact with explosive surface for shot07, PBX3

The impact velocity threshold for PBX3 is shown to be 13.8-16.2 ms^{-1}, this is lower than PBX2. The material response in PBX3 to impact is significantly different to PBX1 and PBX2, brittle failure of the material can be seen early in the penetration, none of the impacts penetrated to pinch with the back face. As the impact velocity is increased the violence of the reaction is far higher for this material.

TABLE 4 – Results for PBX3

Shot	Muzzle Velocity ms^{-1}	Pin Probe Velocity ms^{-1}	Reaction	Spigot Tilt Deg
07	19.6	20.0	Y	1.2
08	15.8	16.2	Y	-
09	12.7	13.8	N	1.0

All the sample materials used were manufactured with the same Type B HMX powder the threshold velocity for reaction was highly dependent on the binder material used. The results show that small changes in the binder material can produce a large change in the behaviour of the consolidated charge. The ignition mechanism in the different materials is different, PBX1 and 2 ignited as the spigot pinched with the rear surface while PBX3 ignited very early in the penetration by the spigot. The violence for all the reactions seen with PBX1 and PBX2 were of similar amplitude, however the violence was seen to increase with impact velocity in PBX3. In no cases was the reaction of a sufficient scale to register on the blast overpressure sensors positioned 1m from around the experiment or to produce a steel flyer from the rear surface

Modelling

HERMES (High Explosive Response to MEchanical Stimulus) has been developed to predict the explosive response to low speed impact. HERMES has been implemented as a material model in the Lagrangian LS-DYNA Finite Element (FE) code. The HERMES model has been applied to simulate the response of the explosive in the spigot test.

Background

The HERMES model comprises several sub models including a constitutive model for strength, porosity and surface area through fragmentation, an ignition model, an ignition front propagation model, and a model for burning after ignition. Thermal effects are not yet explicitly modelled. In the model, ignition is based on a purely mechanical criterion depending on a time integral of a function of the shear, equivalent stress, pressure and strain rate as follows:

$$I_{gn} = \int_0^t \left(2 - \frac{27|s_1 s_2 s_3|}{2Y^3} \right)^5 \left(\frac{p + s_2/2}{P_0} \right)^{1/2} \dot{\varepsilon}_p \, dt \qquad (1)$$

Here $s_{1,2,3}$ are the principal stress deviators, Y is the equivalent stress, p is the pressure, P_0 is a prescribed constant value of pressure, and $\dot{\varepsilon}_p$ is the plastic strain rate. Ignition is deemed to commence when I_{gn} reaches a particular (dimensionless) value, determined by undertaking experiments. Further details are given by Reaugh [V].

Model Predictions

For the case of an impact at 40 m/s, Figure 6 shows the deformation of the explosive PBX1 and the spigot location with contours of the ignition parameter at 200 microseconds after impact. The highest values of the ignition parameter given by equation (1) are in a ring close to the edge of the front face of the spigot. This implies that if ignition occurs, it will occur around the front edge of the spigot. In similar geometry experiments, evidence of ignition in a ring of radius approximately that of the spigot cross-section has been observed through sapphire windows at the back of the explosive [VI,VII]. This is supporting qualitative evidence that ignition of an explosive by a penetrating spigot is indeed driven by the cumulative effects of pressure, shear and plastic deformation – the variables of which the HERMES ignition parameter is an integral function.

It is believed that as the explosive flows around the front of the spigot, high pressures, high strain-rates, and large amounts of shearing occur, which are duly picked up by the ignition parameter integral function (1). As progression to full pinch occurs it is expected that the pressure will increase everywhere in the vicinity of the front of the spigot. The flow of the explosive will depend on the confinement and geometry at this stage and may greatly influence the value of the ignition parameter.

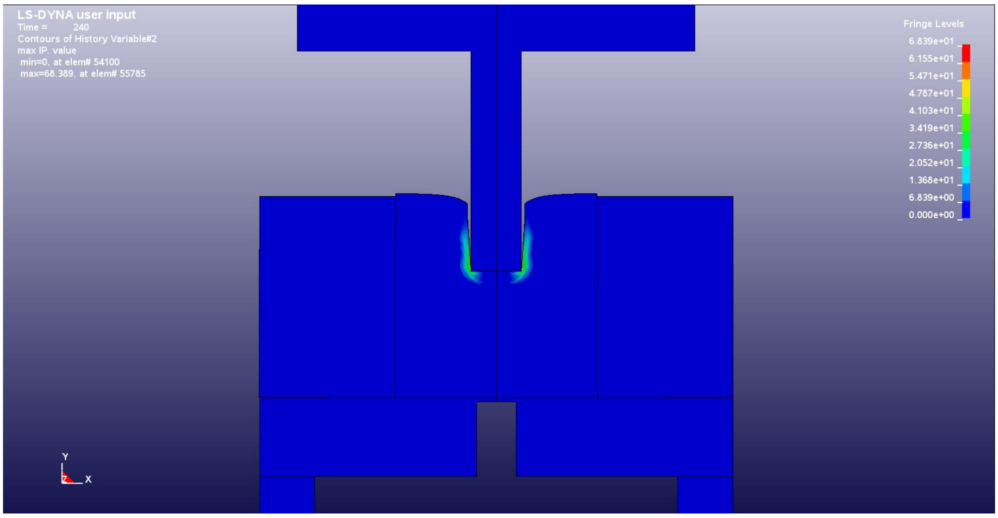


FIG 6 – Contours of the ignition parameter 200 microseconds after an impact at 40 m/s.

The run depicted in Figure 6 failed due to the considerable mesh distortion. The Lagrangian formulation in LS-Dyna is excellent at tracking interfaces between materials, including important frictional forces, while the deformations remain moderate. Extreme deformations can distort the elements to the point where run failure occurs. However, the Lagrangian LS-Dyna code is at least qualitatively predicting the punching of a hole of the size of the spigot in the explosive as seen in experiment. Work is ongoing at LLNL to resolve the mesh distortion problem by integrating HERMES in the ALE3D arbitrary Lagrangian/Eulerian code.

In work on the UK Steven Test [VIII], values of the ignition parameter of the order of 200 were associated with ignition for PBX1. It is not yet clear whether equation (1) is fully independent of the target configuration and subsequently whether the same ignition parameter values are appropriate for this test. In the runs undertaken over the range 10 - 40 m/s no significant burning of the explosive was predicted before the distortion terminates the run and the values of the ignition parameter stay low, which is consistent with the Steven Test results.

The growth in the maximum value of the ignition parameter as a function of spigot penetration distance and impact speed is shown in Figure 7. It is apparent from the plots that the maximum value of the ignition parameter is more sensitive to the depth of penetration than to the impact speed during the early stages of penetration well away from pinch. At higher impact speeds greater pressures, stresses, and plastic strain rates are generated in the explosives than at lower speeds. However at the lower speeds it takes a longer time to reach any given depth of penetration. As a result the integral in equation 1 shows low dependence on the impact velocity during the early stages of penetration by the spigot. The fluctuations seen in the curves are probably artefacts of the mesh distortion associated with the extreme deformations and of estimation from the contour plots. It is not yet known whether the value of the ignition parameter would eventually increase to the values corresponding to ignition seen in the Steven Test as pinching of the explosive is achieved when the spigot almost fully penetrates it. This is an important question that will be the subject of future research.

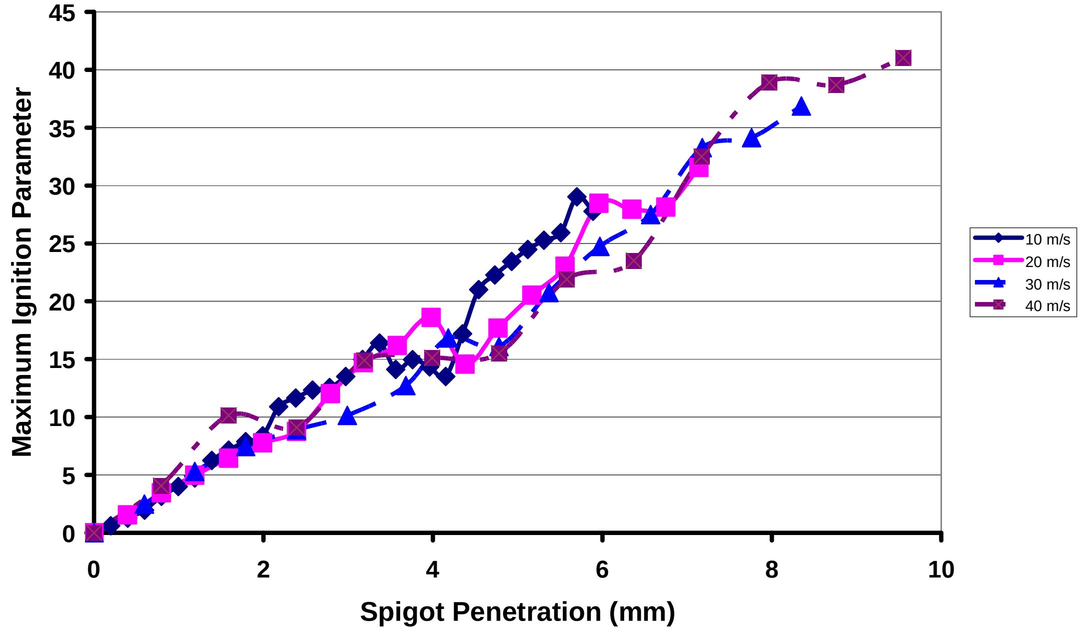


FIG 7 – Dependence of growth in maximum ignition parameter upon impact speedparameterupon depth of penetration of the spigot.

Conclussion

Experiments on three different HMX based explosives have been undertaken to investigate the threshold of reaction for a small diameter spigot. The threshold of reaction for two of the materials has been found, 19.0 – 21.6 ms^{-1} for PBX2 and slightly lower at 13.8-16.2 ms^{-1} for PBX3. The threshold for PBX1 is below 14.2 ms^{-1}. These materials show a different mechanism for initiation, PBX1 and PBX2 ignite as the spigot pinches with the steel back plate, whilst PBX3 ignites as the spigot penetrates the material.

A model has been developed which gives qualitative agreement between experimental results and predictions. To date with the Lagrangian formulation the onset of mesh distortion prior to significant burning prevents full quantitative validation against experiment. To achieve quantitative validation, in further work it is planned to integrate HERMES in the LLNL code ALE3D.

Acknowledgments

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